

Volcanic Risk Studies for the U.S. and Japanese Geologic Repository Programs

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The major concern surrounding storage of high-level radioactive waste in a geologic repository is the possible release of radionuclides to the environment. The most likely mechanism for such a release is by gradual dissolution of waste, followed by transport of radionuclides in groundwater. In tectonically active regions, another mechanism, a volcanic eruption, might directly or indirectly lead to radionuclide release. Since the early 1980s, we have assessed volcanic risk as it relates to the potential U.S. repository for storage of high-level radioactive waste at Yucca Mountain, Nevada, and more recently, for the Japanese high-level waste disposal program.

As the lead Department of Energy team for volcanic hazard studies for the Yucca Mountain Site Characterization Project (YMP), we have developed methods for assessing the probability of volcanic disruption of the potential repository and for assessing the consequences of a volcanic disruption, primarily by conducting studies of analog volcanic systems. These studies ended in 1996. In the past two years, we have focused on supporting the YMP Site Recommendation and License Application by analyzing and integrating new information with previous studies.

Since 1998, we have expanded on our Yucca Mountain work by conducting volcanic risk studies for the Japan Nuclear Cycle Development Institute (JNC) to support the Japanese geologic repository program. Using an analog composite volcano, Summer Coon, in southwestern Colorado, we have assessed the hazard and consequences of a composite volcano disrupting a Japanese geologic repository.

Yucca Mountain Project Studies

The need to assess the possibility of a volcanic eruption disrupting the potential repository at Yucca Mountain is driven by the occurrence of eight small-volume ($<1 \text{ km}^3$) Quaternary ($<1.6 \text{ million years}$) basaltic

volcanoes within 50 km of Yucca Mountain. Six of these volcanoes lie within 20 km of the repository site (Figure 1). For our site characterization studies for the YMP, we have used geochronology techniques to establish the age and recurrence rate

of volcanism and field and geochemistry studies to understand the mechanisms of volcano formation in the region.

Determining the ages of volcanoes older than approximately 1 million years has been relatively straightforward

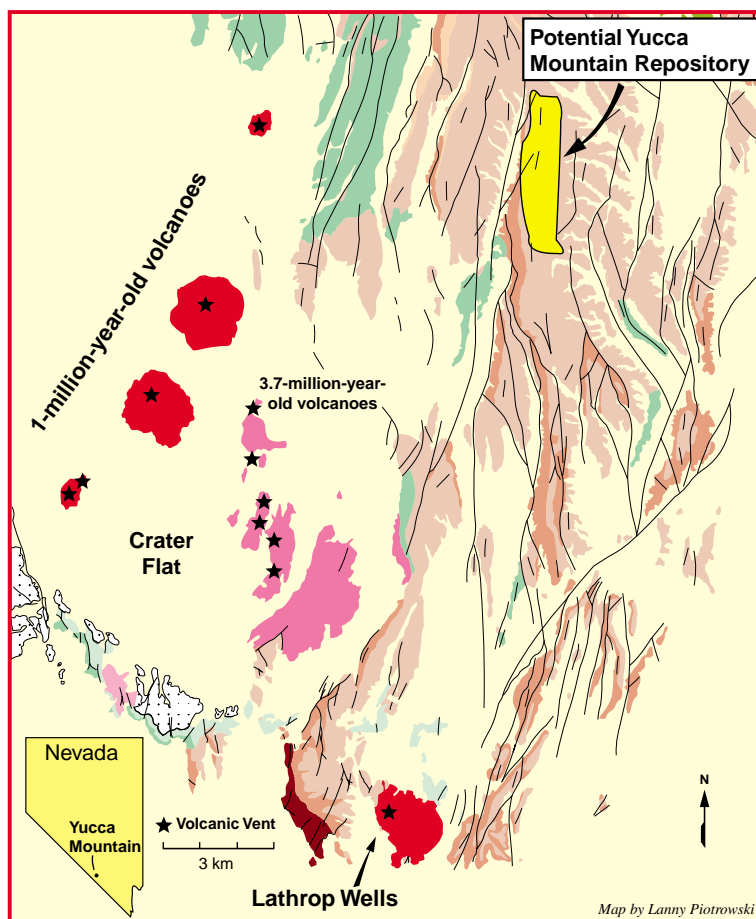


Figure 1. Volcanoes Near Yucca Mountain.

A dozen volcanoes are within 20 km of the potential repository site. Six volcanoes have been active within the last million years; the other six, within the last 4 million years. The youngest volcano, at Lathrop Wells, is 75,000 years old.

ward using $^{40}\text{Ar}/^{39}\text{Ar}$ techniques. Determining a reliable age for the Lathrop Wells, the youngest volcano near Yucca Mountain, has been technically challenging. We have applied multiple chronology techniques, which have yielded ages ranging from approximately 10,000 to 150,000 years. Using $^{40}\text{Ar}/^{39}\text{Ar}$ isotopic methods to date both whole-rock basalt and thermally reset sanidine from tuff xenoliths, we have determined only recently that Lathrop Wells is approximately 75,000 years old.

Probabilistic Methods. For the YMP, our major goal has been to assess the probability that magmatic processes will disrupt the potential repository during the performance period of waste containment (10,000 years as set by the Environmental Protection Agency regulation). Using results of site characterization studies of Yucca Mountain as the geologic framework, we estimated the probability that a new volcano will form in the Yucca Mountain region over the next 10,000 years. Given that a new volcano does form, we determined the probability that it will disrupt the repository.

We expressed the probability of magmatic disruption as the annual probability that a volcanic event will disrupt (or intersect) the repository, conditional on a volcanic event occurring during the time period of concern. In its simplest form, the probability of disruption is calculated by multiplying the recurrence rate of volcanism by the intersection ratio (repository area/area in which volcanism occurs), taking into account uncertainties in each value. We formulated the disruption of a repository by a volcanic event as a conditional probability

$$\text{Pr}_{\text{dr}} = \text{Pr}(E2 \text{ given } E1)\text{Pr}(E1),$$

where Pr_{dr} is the probability of magmatic disruption of a repository, $E1$ denotes the rate of occurrence of volcanic events, defined as the formation of a *new* small-volume

basaltic volcanic center in the Yucca Mountain area, and $E2$ is the probability of intersection of the repository or repository area by that volcanic event. This probability is expressed mathematically as

$$\text{Pr}[\text{no magmatic event before time } t] = \exp(-ltp),$$

where l is the recurrence rate, t is time, and p is the probability that an event is disruptive. This probability model assumes a homogeneous Poisson distribution of volcanic events in space and time. Critical assumptions of a Poisson distribution are that the events occur independently, they are exponentially distributed in time t , and the probability of more than one event occurring at the same time is vanishingly small.

Our early calculations of the annual probability of magmatic disruption of the Yucca Mountain Site produced estimates of between 5×10^{-8} to 3×10^{-10} disruptions per year (Figure 2). It is important to note that these calculations were conducted in the early 1980s, while the YMP was still in the initial stages of site characterization studies. Our estimates, along with those of researchers at Sandia National Laboratories and the U.S. Geological Survey, led to general, but not universal, acceptance that the Yucca Mountain site would not be disqualified as a location for a repository because of the risk of volcanic hazards.

Our volcanism studies at Los Alamos continued through the mid-1990s, while the YMP shifted its emphasis from site characterization studies to constructing an exploratory test facility at the site. During this interval, an attempt was made to complete probability modeling through application of Monte Carlo simulation modeling. We used Monte Carlo simulation modeling to examine each attribute of the conditional probability model systematically. Both the recurrence rate and the disruption ratio were assessed using all combinations of alternative

models, including models developed by the State of Nevada and the Nuclear Regulatory Commission.

We modified the resulting probability distributions to eliminate combinations of spatial and structural models that excluded volcanic events. This important effect was not included in probability calculations where $E1$ and $E2$ were independently estimated. The modified matrix of probability distributions was solved using simulation modeling to give aggregate distributions of the annual probability of disruption for a repository block in Yucca Mountain. Our results indicated that the mean probability of disruption of the potential YMP repository is $1.9 \times 10^{-8} \pm 1.6 \times 10^{-8}$ per year.

In an attempt to bring probability estimates to resolution, the DOE convened a formal expert judgment panel in 1995 to independently assess the probability of volcanism at Yucca Mountain. A 10-member panel of volcanism experts nominated by their scientific peers was assembled, and the panel completed a probabilistic volcanic hazard assessment (PVHA).

Each panel member independently estimated probability distributions, which were then aggregated. The aggregate result yielded a mean annual probability of magmatic disruption of 1.5×10^{-8} , with a 90-percent confidence interval of 5.4×10^{-10} to 4.9×10^{-8} . The mean and confidence interval of this distribution was virtually identical to our previous probability estimates, as can be seen in Figure 2.

Analog Studies

To conduct a comprehensive risk assessment, one must know both the probability and the consequences of volcanic events. For our first type of consequences study, we attempted to constrain the amount of debris that could be exhumed from repository depths by studying the concentration and composition of shallow crustal

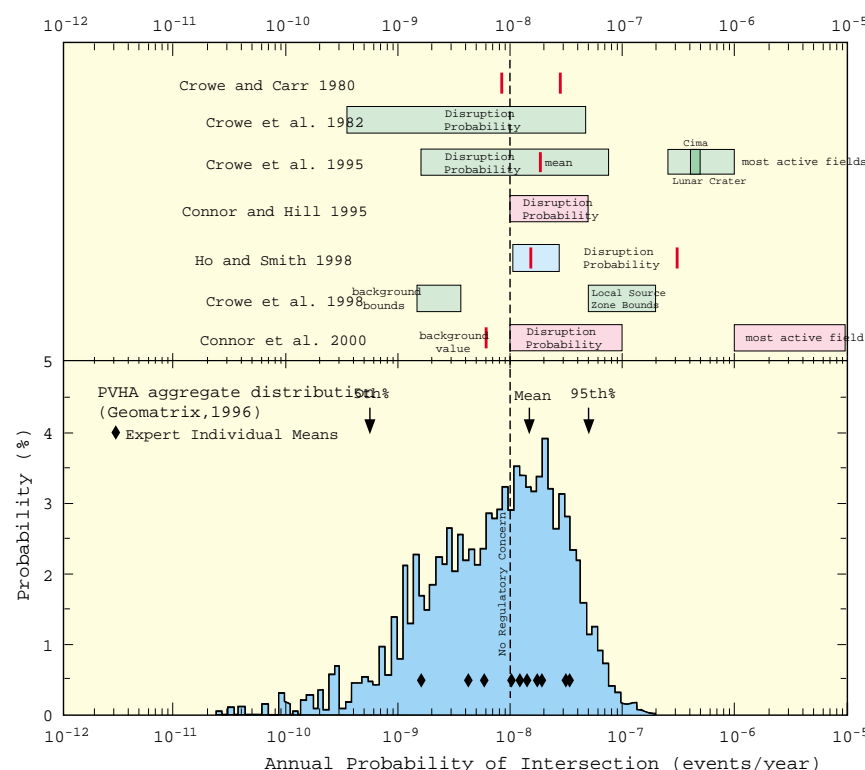


Figure 2. Probability of Future Volcanic Activity at Yucca Mountain.

A number of researchers has analyzed the likelihood of a volcano disrupting a repository at Yucca Mountain. Their probability point estimates (single lines) and ranges (rectangles) are compared here with estimates made by a panel of experts convened by the DOE to assess the hazard (PVHA distribution). The ranges labeled “most active fields” and “Local Source Zone Bounds” represent upper bounds for the probability and assume that the repository is placed in an active volcanic field. The background bounds and value represent lower bounds that assume the repository does not lie in an active volcanic field but lies in a region that produces only sporadic eruptions. Most estimates put the disruption probability at a little greater than 10^{-8} events per year, which translates to a 1 in 7000 chance that volcanic activity could disrupt the repository.

xenoliths at several analog volcanoes that encompass the range of eruptive processes that might occur in the Yucca Mountain region. These analog volcanoes are located in areas in which there are good constraints on subsurface, layer-cake geology from a combination of regional exposures and water and petroleum wells. This fact enabled us to quantify the erosion of wall rock as a function of depth and eruptive process.

Unfortunately, the applicability of these studies has decreased with the recent changes in repository design, in which the waste packages will sit in open, rather than backfilled, drifts. This new design raises the possibility that, given an igneous event at the repository (with or without an

attendant eruption), hundreds to thousands of waste packages could be partially destroyed by explosive fragmentation of magma into the drifts. The largest potential effect of destroying the integrity of the waste packages this way is on the subsequent groundwater transport of dissolved radionuclides.

In our second type of analog study, we focused on the hydrothermal and mechanical effects associated with intrusion of basalts into silicic tuffs. Results of studies in which the host tuffs are both vitric and altered suggest that alteration is limited to within a few meters of the tuff-basalt contacts. These studies are being reopened from a new perspective, and we are using the

sites as analogs to study the effects of repository thermal loading (from radioactive decay) on the surrounding rocks.

Studies for the JNC

The Japanese islands are in a complex plate-tectonic setting, and as a result, they are one of the more tectonically and volcanically active areas on the Earth. Approximately 350 volcanoes have been active in Japan in the past 2 million years. Thus, within the next 100,000 years, it can be expected that several new volcanoes will form in Japan. In terms of volcanism, we must consider two primary factors when selecting the site for a geologic repository in Japan. These factors are (1) the rate of new volcano formation in a particular region and (2) the distance at which a volcano presents a hazard to a nearby repository.

As part of our studies for the JNC, we used the Oligocene Summer Coon volcano in southern Colorado, with its well-exposed system of radial dikes (Figure 3), as an analog for similar composite volcanoes in Japan. Using Summer Coon, we were able to estimate the probability of repository disruption by a radial dike system, conditional on a volcano forming nearby.

Erosion has removed much of the original volcanic edifice at Summer Coon, exposing an extensive radial dike system that is probably typical of large composite volcanoes in Japan. Intruding early mafic cone-breccia deposits are numerous (>100–200) at Summer Coon; and basaltic andesite and andesite (mafic) dikes with typical widths of 1 to 3 m are also present. Intruding both the early mafic and silicic cone breccias are about 25 dacite (silicic) dikes with typical widths of 10 to 20 m. The silicic dikes are on the average longer than the mafic dikes (Figure 3) and form prominent topographic features.

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We developed a Monte Carlo simulation model that estimates the probability of dike intersection as a function of (1) distance from the center of a composite volcano, (2) repository area, and (3) radial dike density and length. Although we have assessed the hazard of a dike intersecting a geologic repository for the case of small-volume basaltic volcanism at Yucca Mountain, we are not aware of any previous analysis of the hazard to a repository from the radial dike system of a large composite volcano.

Summer Coon Studies. To estimate the conditional probability that a dike from a new volcano will intersect a repository, we estimated the number of dikes and their spatial distribution, the distribution of dike lengths, and the area and shape of the repository. We based the number of dikes on dike counts at Summer Coon, and we chose a log-normal distribution to represent both the mafic and the silicic dike-length distributions, based on dike-length data from Summer Coon. For the repository area, we used two values, 4 km² and 8 km², that encompass a range of areas typically proposed for repository designs internationally; and for geometric simplicity, we assumed that the shape was circular.

The mathematical logic for the probability model is based on the trigonometry of a right triangle (Figure 4). The probability model was programmed (using Microsoft Excel Visual Basic and Decisioneering Crystal Ball add-in functions for Excel) to sample probability distributions using Monte Carlo simulation. The model simulates the geometry of dike emplacement and tests for two conditions, which, if true, result in a dike intersection of a repository: (1) Does the radial dike have an orientation that could result in a dike intersection (i.e., is within the angle 2θ)? (2) If the first condition is true, is the dike long enough to intersect the repository?

A single Monte Carlo realization of a complete radial dike emplacement (120 mafic dikes, 30 silicic dikes) is shown in Figure 4. For the Summer Coon cases, 1,000 realizations of the Monte Carlo simulation were run for each combination of distance and repository area calculated. In addition, a bounding case was run based on fissure length data from Mount Etna, to assess the effect of a larger radial dike system on the probability of intersection. Finally, sensitivity calculations were run (using 2,500 realizations) to assess the effect of doubling mean dike length, standard deviation of the dike length, dike density (number of dikes), and repository area.

Results are presented as the conditional probability of intersection calculated at incremental distances from the volcano center (Figure 5). Sensitivity calculations to assess the effect of doubling each of the key parameters are presented as the relative change from the base case for silicic dikes (Figure 5, inset).

Separate probabilities of intersection were calculated for the mafic and silicic dike sets at Summer Coon for both a 4 km² and an 8 km² repository (Figure 5). In all cases, the probability values decline rapidly with distance from the volcano due to the decrease in dike density dictated by the divergence of radial dikes away from the volcano center (Figure 4).

Although the silicic dikes are longer on average than the mafic dikes, they are also less numerous, causing the probability curves for mafic and silicic dikes to cross at distances of 5 to 6 km from the volcano center (Figure 5). At 4 km and less, the probability of intersection is 1 for the mafic dike set because of high dike density. For the longer, silicic dike set, a probability of 1 is reached at a distance of 2 or 3 km, depending on the repository area.

The shorter length and smaller dispersion in the length of the mafic dikes result in a steeper drop in probability values compared to the

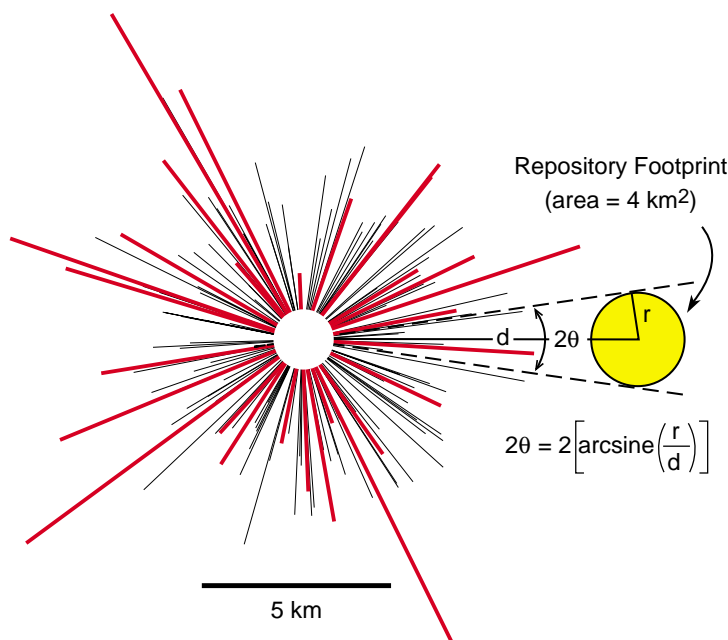


Figure 4. Mathematical Basis for Monte Carlo Simulation of Probability of Dike Intersection.

Probability of dike intersection is dependent upon the dike density and length on the area of the repository (dependent on the radius, r), which, together with distance to the volcano (d), define the 2θ angle that dikes must fall within to be able to intersect the repository. An example of a single simulation realization is shown, using the dike length parameters from Figure 2, assuming 120 mafic dikes, 30 silicic dikes, and a uniform radial distribution of dike orientations.

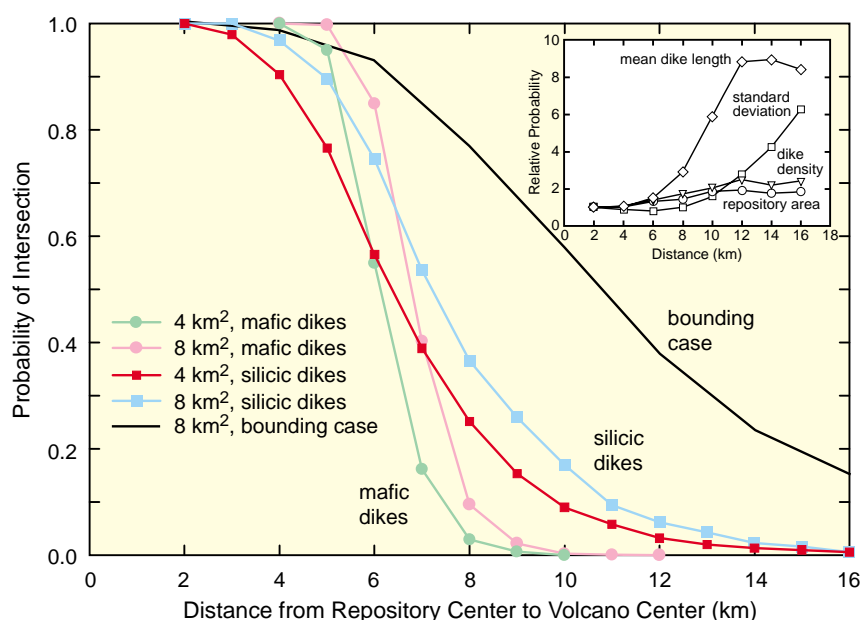


Figure 5. Distance of the Repository Center from the Volcano Center Versus the Probability of Dike Intersection of a Repository.

Probability of intersection for both mafic and silicic dikes based on data from Summer Coon volcano are shown, as well as a bounding case using dike lengths approximately double those of silicic dikes at Summer Coon. Results are shown for repository areas of 4 and 8 km². Inset shows sensitivity of the probability of dike intersection (expressed as relative probability compared to the base case for silicic dikes at Summer Coon and a repository area of 4 km²) to doubling of dike length, dike density, and repository area. The probability of intersection is most sensitive to dike length and relatively insensitive to repository area or dike density.

silicic dikes; the probability of intersection is $<10^{-2}$ beyond 10 km distance for both repository cases. Conversely, the longer length and larger dispersion in the length of the silicic dikes results in a more gradual drop in probability values with distance. The probability of intersection for silicic dikes is $\leq 10^{-2}$ at ~14- to 15-km distance and $\leq 10^{-4}$ at 30-km distance for both repository cases.

Scientists in Japan have used several criteria to assess the distance at which a volcano can perturb the surrounding geologic environment. These criteria include geothermal gradient, heat flow, size of hydrothermal convection systems, pH and anion index of hot springs, and ³He/⁴He of groundwater. Collectively, these criteria suggest that the geologic environment is not perturbed beyond about 15 km from an existing volcano.

The results of our assessment

indicate that the conditional probability of a radial dike intersecting a repository is $<10^{-2}$ beyond a distance of approximately 15 km from the center of a typically sized composite volcano. The Japanese data and our probabilistic assessment suggest that the volcanic hazard to a geologic repository is minimal if the new volcano forms at a distance greater than about 15 to 20 km from the repository. ■

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Further Reading

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